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NEUTRINO MAGNETIC MOMENTS AND THE SOLAR NEUTRINO PROBLEM *

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Abstract

Present status of the neutrino magnetic moment solutions of the solar neutrino problem is reviewed. In particular, we discuss a possibility of reconciling different degrees of suppression and time variation of the signal (or lack of such a variation) observed in different solar neutrino experiments. It is shown that the resonant spin–flavor precession of neutrinos due to the interaction of their transitions magnetic moments with solar magnetic field can account for all the available solar neutrino data. For not too small neutrino mixing angles ($\sin 2\theta_0 \gtrsim 0.2$) the combined effect of the resonant spin–flavor precession and neutrino oscillations can result in an observable flux of solar $\bar{\nu}_e$'s.

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1 Introduction

The solar neutrino problem, i.e. the deficiency of the observed flux of solar neutrinos as compared to the predictions of the standard solar model, remains one of the major unresolved puzzles of modern physics and astrophysics. Although the astrophysical solution of the problem is not yet completely ruled out, it is very unlikely to be the true reason of the discrepancy provided all the experimental data (and in particular, the results of the Homestake experiment for the whole period of its operation) are taken seriously. It is for this reason that the particle–physics solutions to the problem are currently considered to be more favorable [1, 2, 3].

There are several possible neutrino–physics solutions of the solar neutrino problem, the most popular one being resonant neutrino oscillations in the matter of the sun (the MSW effect [4]). In my talk I will concentrate, however, on another type of solutions related to possible existence of large magnetic or transition magnetic moments of neutrinos. In this case neutrino spin precession [5, 6] or spin–flavor precession [6, 7, 8] can occur in the magnetic field of the sun, converting a fraction of solar ν_{eL} into ν_{eR} or into $\nu_{\mu R}$, $\nu_{\tau R}$, $\bar{\nu}_{\mu R}$ or $\bar{\nu}_{\tau R}$. Although $\bar{\nu}_{\mu R}$ and $\bar{\nu}_{\tau R}$ are not sterile, they cannot be observed in Homestake, SAGE and GALLEX experiments and can only be detected with a small cross section in the Kamiokande experiment. Spin–flavor precession of neutrinos can be resonantly enhanced in the matter of the sun [7, 8], in direct analogy with the MSW effect. Neutrino spin precession and resonant spin–flavor precession (RSFP) can account for both the deficiency of solar neutrinos and time variations of the solar neutrino flux in anticorrelation with solar activity for which there are some indications in the Homestake data. This comes about because the toroidal magnetic field of the sun is strongest in the periods of active sun.

Some remarks about time structure of the Homestake data are in order. The data compares better with an assumption of a time–dependent signal than with that of a constant one, hinting to an anticorrelation with solar activity. The existing analyses of the data using different statistical methods gave fairly big values of the correlation coefficient between the

data and sun–spot number [9, 10, 11, 12, 13]. These analyses, however, were performed before 1990 and so did not take into account more recent runs 109-126. These runs do not show a tendency to vary in time, similarly to runs 19–59. A recent analysis of Stanev [14] which updated the one of ref. [10] included the runs 109-126 and showed that this results in the correlation coefficient being decreased by an order of magnitude as compared to the previously obtained one, but the correlation probability is still large: confidence level of the correlation with the sunspot number s is 0.96 instead of 0.996, and that of the correlation with $s|z|$ where z is the latitude of the line of sight is 0.99 instead of 0.9993. The correlation with the 22-yr cycle is even better than the correlation with the 11-yr one. Therefore, the possibility that the solar neutrino flux anticorrelates with solar activity still persists and deserves further study.

At the same time, the Kamiokande group did not observe any time variation of the solar neutrino signal in their experiment, which allowed them to put an upper limit on the possible time variation, $\Delta Q/Q < 30\%$ at 90% c.l.. Therefore a question naturally arises as to whether one can reconcile a strong time variation in the Homestake experiment with a small (or no) time variation in Kamiokande. Recently, it has been shown [15] (see also [16, 17, 18] that the RSFP scenario is capable of accounting for all the existing solar neutrino data, including their time structure or lack of such a structure. In particular, it can explain mild suppression of the flux in the gallium experiments and naturally reconcile strong time variations of the signal observed in the Homestake experiment with small time variations allowed by the Kamiokande data. Let me now briefly describe how this works.

2 GALLEX and SAGE

Although the gallium solar neutrino experiments SAGE and GALLEX have been operating for too short a time and so are unable to confirm or disprove 11-yr variations of the signal, they still provide us with an information which is relevant for the magnetic moment sce-

narios. The point is that most of the data have been taken during the period of high solar activity. One could therefore expect a strong suppression of the signal in the gallium experiments, which has not been observed. This disfavors the ordinary spin precession scenario since it is neutrino-energy independent and so predicts the same degree of suppression and time variation of the signal in all the solar neutrino experiments. At the same time, the resonant spin–flavor precession (RSFP) is strongly energy dependent and so naturally results in different suppressions and time variations in different experiments. In particular, the *pp* neutrinos which are expected to give the major contribution to the signal in the gallium experiments, have low energies and so should encounter the RSFP resonance at high densities, somewhere in the radiation zone or in the core of the sun (since the resonant density is inversely proportional to neutrino energy). We know that the magnetic field does exist and may be quite strong in the convective zone of the sun ($0.7R_\odot \leq r \leq R_\odot$). However, it is not clear if strong enough magnetic field can exist deeper in the sun, i.e. in the radiation zone or in solar core. If the inner magnetic field of the sun is week, the RSFP will not be efficient there and the *pp* neutrinos will leave the sun intact, in accordance with the observations of GALLEX and SAGE. One can turn the argument around and ask the following question: If we believe in the RSFP mechanism, what is the maximal allowed inner magnetic field which is not in conflict with the gallium experiment? The answer turns out to be $(B_i)_{max} \approx 3\times 10^6$ G assuming the neutrino transition magnetic moment $\mu = 10^{-11}\mu_B$ [15].

3 Reconciling Homestake and Kamiokande data

It is more difficult to explain how one can reconcile strong time dependence of the signal observed in the Homestake experiment with no or very little time variation of the Kamiokande data. The key points here are that [19, 20, 21, 15]

(1) The two experiments are sensitive to slightly different parts of the solar neutrino spectrum: Homestake is sensitive to both energetic ^{8}B neutrinos and medium–energy ^{7}Be

and *pep* neutrinos, whereas the Kamiokande experiment is only sensitive to the high–energy part of ^{8}B neutrinos ($E > 7.5$ MeV);

(2) For Majorana neutrinos, the RSFP converts left–handed ν_e into right–handed $\bar{\nu}_\mu$ (or $\bar{\nu}_\tau$) which are sterile for the Homestake experiment (since their energy is less than the muon or tauon mass) but do contribute to the event rate in the Kamiokande experiment through their neutral–current interaction with electrons. Although the $\bar{\nu}_\mu e$ cross section is smaller than the $\nu_e e$ one, it is non-negligible, which reduces the amplitude of the time variation of the signal in the Kamiokande experiment.

It turns out that the above two points are enough to account for the differences in the time dependences of the signals in the Homestake and Kamiokande experiments. The calculated event rates in the Homestake and Kamiokande experiments decrease with increasing convective zone magnetic field until they reach their minima, and then start to increase. The minimum of the Kamiokande signal is situated at a lower magnetic field then the one of the Homestake signal due to the energy dependence of the RSFP and the above point (1). Also, it is shallower than the minimum of the Homestake signal due to the point (2). For these reasons, for a certain range of variation of the solar magnetic field $B_\perp$ the Homestake signal can decrease significantly with increasing $B_\perp$ whereas the Kamiokande signal is near its minimum and therefore does not change much [20, 21, 15].

4 Fitting the data

In a recent paper [15] all the available solar neutrino data have been analyzed in the framework of the RSFP disregarding neutrino mass mixing. However, in the general case one should include neutrino mixing effects as well. The motivation for that is as follows:

(1) RSFP requires non-vanishing flavor-off-diagonal neutrino magnetic moments, i.e. implies lepton flavor non-conservation. Therefore neutrino oscillations *must* also take place. In general one should therefore consider the RSFP and neutrino oscillations (including the

MSW effect) jointly. The results of ref. [15] are only valid in the small mixing angle limit.

(2) It has been shown in [15] that all the existing solar neutrino data can be fitted within the RSFP scenario for certain model magnetic field profiles and certain values of neutrino parameters μ and Δm^2. It would be interesting to see how the neutrino mixing modifies these results.

(3) In ref. [22] it has been suggested that the combined action of the RSFP and MSW effect in the convective zone of the sun can relax the lower limit on the product $\mu B_\perp$ of neutrino magnetic moment and solar magnetic field required to account for the data. The main idea was that the MSW effect can assist the RSFP to cause the time variations of the neutrino flux by improving the adiabaticity of the RSFP (this can occur when the RSFP and MSW resonances overlap). It would be interesting to confront this idea with the new experimental data.

Combined action of the RSFP and the MSW effect on solar neutrinos has been considered in a number of papers [8, 23, 24, 25, 26]. However, the data of the gallium experiment were not available that time. We therefore re-analyzed all the available solar neutrino data in the framework of the RSFP scenario taking into account possible neutrino mixing and oscillations effects [27]. It was assumed that the $\nu_e - \nu_\mu$ mixing is generated by a Majorana neutrino mass term, and that there exists a $\nu_{eL} - \bar{\nu}_{\mu R}$ transition magnetic moment μ. The evolution equation for a system of two Majorana neutrinos and their antiparticles in the flavor basis is

$$i\frac{d}{dt}\begin{pmatrix} \nu_{eL} \\ \bar{\nu}_{eR} \\ \nu_{\mu L} \\ \bar{\nu}_{\mu R} \end{pmatrix} = \begin{pmatrix} N_1 - c_2\delta & 0 & s_2\delta & \mu B_\perp \\ 0 & -N_1 - c_2\delta & -\mu B_\perp & s_2\delta \\ s_2\delta & -\mu B_\perp & N_2 + c_2\delta & 0 \\ \mu B_\perp & s_2\delta & 0 & -N_2 + c_2\delta \end{pmatrix} \begin{pmatrix} \nu_{eL} \\ \bar{\nu}_{eR} \\ \nu_{\mu L} \\ \bar{\nu}_{\mu R} \end{pmatrix} \tag{1}$$

Here $B_\perp(t)$ is the transverse magnetic field,

$$N_1 \equiv \sqrt{2}G_F(n_e - n_n/2), \quad N_2 \equiv \sqrt{2}G_F(-n_n/2), \quad \delta \equiv \Delta m^2/4E,$$

$$s_2 \equiv \sin 2\theta_0, \quad c_2 \equiv \cos 2\theta_0, \tag{2}$$

where G_F is the Fermi constant, n_e and n_n are the electron and neutron number densities, the rest of the notation being obvious. The zeros in the effective Hamiltonian in eq. (1) are related to the fact that diagonal magnetic moments of Majorana neutrinos are precluded by CPT invariance.

We have calculated the neutrino signals in the chlorine, gallium and Kamiokande experiments using ten different model magnetic field profiles (see [27] for more details). The results of our analysis are briefly summarized below.

(1) For small mixing angles, $\sin 2\theta_0 \lesssim 0.1$, the results of our previous study [15] are only slightly modified.

(2) For moderate mixing angles, $\sin 2\theta_0 \gtrsim 0.2$, some of the magnetic field profiles which proved to give good fit of the data for vanishing θ_0, no longer work: they result in too strong a suppression of the signal in the gallium experiments since the adiabaticity of the MSW effect for the low–energy *pp* neutrinos gets too good. Reasonable fit can still be achieved for very large mixing angles, $\sin 2\theta_0 \approx 1$, but in this case a large flux of electron antineutrinos would be produced in contradiction with an upper limit derived from the Kamiokande and LSD data [28, 29] (see below, point (5)).

(3) Possible way out of this situation is to use the model magnetic field profiles with their maximum being shifted towards the outer regions of the convective zone. This would require lower values of of Δm^2 for the RSFP to be efficient, which in turn would decrease the adiabaticity of the MSW effect, and the flux of the *pp* neutrinos will be essentially unsuppressed. We have tried three such new magnetic field configurations and they produced good fit of all the data.

(4) Typical values of the neutrino parameters required to account for the data are $\Delta m^2 \simeq (10^{-8}\text{–}10^{-7})$ eV^2, $\sin 2\theta_0 \lesssim$ 0.2–0.4, depending on the magnetic field configuration; for neutrino transition magnetic moment $\mu = 10^{-11}\mu_B$ the maximum magnetic field in the solar convective zone should vary in time in the range (15–30) kG.

(5) As have been noticed above (points (2) and (3)), some magnetic field configurations which used to give a good fit to the data for vanishing θ_0, no longer do so for not too small mixing angles and, conversely, some other profiles which failed to reproduce the data for $\theta_0 = 0$ do give a good fit for moderate θ_0. This is, in fact, a rather unpleasant situation: whether or not a given magnetic field profile fits the data depends on the neutrino mixing angle which is unknown. Possible way out is to look for the $\bar{\nu}_{eR}$ signal from the sun. The point is that if neutrinos experience the RSFP in the sun and also have mass mixing, a flux of electron antineutrinos can be produced which is in principle detectable in the SNO, Super–Kamiokande and Borexino experiments even in the case moderate neutrino mixing angles [8, 23, 26, 30, 31]. The main mechanism of the $\bar{\nu}_{eR}$ production is $\nu_{eL} \to \bar{\nu}_{\mu R} \to \bar{\nu}_{eR}$, where the first transition is due to the RSFP in the sun and the second one is due to the vacuum oscillations of antineutrinos on their way between the sun and the earth. The salient feature of this flux is that it should vary in time in *direct* correlation with solar activity. The detection of the solar $\bar{\nu}_{eR}$ flux would be a signature of the combined effect of the RSFP and neutrino oscillations. It could allow one to discriminate between small mixing angle and moderate mixing angle solutions.

The $\bar{\nu}_{eR}$ flux can be significantly enhanced if the solar magnetic field changes its direction along the neutrino trajectory [32, 33, 34]. In this case one can have a detectable $\bar{\nu}_{eR}$ flux even if the neutrino magnetic moment is too small or the solar magnetic field is too weak to account for the solar neutrino problem [34, 35].

To summarize, the RSFP is a viable scenario which is capable of accounting for all the presently existing solar neutrino data, including their time structure (or lack of such a structure). It also gives very specific predictions for the forthcoming solar neutrino experiments, such as strong time dependence of the ^{7}Be neutrino flux, absence of a suppression and time variation in the neutral–current events at SNO, and an observable flux of solar $\bar{\nu}_{eR}$'s for moderate neutrino mixing angles.

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